Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

A56.9 R31

Soil Moisture (III) Type Ex.

Measurement of
Soil Moisture Content
by the Neutron Method

August 1958 ARS 41-24
Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

C O N T E N T S

	Page
Glossary	ii
Introduction	1
Principle	1
Equipment	5
Fast Neutron Source	5
Detector of Slow Neutrons	6
Counting Device (Scaler)	9
Calibration or Standard Bucket	11
Access Tubes	12
Cable	12
Operation	14
Depth Adjustment	14
Standardization	14
Measurements	16
Resolution, Calibration, and Precision	17
Resolution	17
Calibration	17
Precision	23
Health Hazard	24
General Discussion and Summary	26
Acknowledgments and Note	27
References	28

G L O S S A R Y

Alpha particle	-	Particle consisting of two protons and two neutrons; weight 4; charge +2; emitted by certain nuclei; also: Helium ^{4} nucleus.
Beta particle	-	Electron; emitted by certain nuclei.
Disintegration	-	Spontaneous emission by a nucleus of either alpha or beta particles.
Dose	-	Quantity of ionizing radiative energy absorbed by the body, or parts thereof, per unit of mass. Expressed in rem or mrem (roentgen or milliroentgen equivalent man). For gamma radiation 1 rem or 1 mrem is equivalent to 1 r (roentgen) or 1 mr.
Exposure	-	Intensity of absorption of ionizing radiation by the body. Expressed in rem per hr or any other appropriate time unit.
Flux	-	Number of particles crossing a unit of area per unit of time.
Gamma radiation	-	Electromagnetic, ionizing radiation emitted by the nucleus.
Half life	-	Time required to reduce the quantity of a radioisotope to one half of the original amount.
Input sensitivity	-	Smallest signal which will be registered by a system.
Isotope	-	Chemical element of a single atomic mass.
Mev	-	Million electron volt: the kinetic energy imparted to an electron by a potential difference of a million volts.
Millicurie	-	A quantity unit of radioactive material equivalent to 3.7×10^7 disintegrations per second; also equivalent to 1 mg of Radium.
Milliroentgen	-	A unit of ionizing radiative energy; one thousandth of a roentgen.
Neutron	-	Elementary nuclear particle; mass 1; charge 0.

Proton	-	Elementary nuclear particle; mass 1; charge +1; also: hydrogen ion.
Radiation level	-	Intensity of ionizing radiation; expressed in roentgen or milliroentgen per unit time.

(Note: Radiation terminology taken from: Title 10 - Atomic Energy, Chapter 1 - Atomic Energy Commission, Part 20 - Standards for protection against radiation. Federal Register, January 29, 1957, pp. 548-554).

MEASUREMENT OF SOIL MOISTURE CONTENT BY THE NEUTRON METHOD

by

C. H. M. van Bavel 1/

INTRODUCTION

The purpose of this report is to acquaint field workers in soil and water conservation research with the neutron method for measuring soil moisture. This is attempted here in simple terms, details of physical or mathematical nature being omitted.

Furthermore, this report gives recommended equipment needs and suggestions for its use. Finally, a discussion of the advantages and limitations of the method is presented as well as pertinent information on precision and calibration.

By this time the neutron method is by no means new. In 1950 first reports were published; these have been followed by many others. As research progressed, various aspects of the method have become more clear and at this time definite measurement techniques can be recommended to the field research worker who is anxious to use the method but not interested in improving or investigating it. A list of the most important literature contributions is given in the back of this report.

No attempt will be made to review research done in the past or to consider the pros and cons of the different instrumentation solutions that have been suggested, except as it seems advisable for achieving the purpose of this report.

PRINCIPLE

The neutron method is a measurement of the number of hydrogen nuclei that are present per unit volume of soil. Therefore, it is a means of directly observing the moisture content by volume. The physical principle is as follows.

1/ Soil Scientist, Soil and Water Conservation Research Division, Agricultural Research Service, U.S.D.A., at 324 Williams Hall, N. C. State College, Raleigh, North Carolina.

A small source of fast neutrons can be made by intimate mixture of an alpha (helium nucleus) emitter and beryllium. A Ra-Be source is an example of such a mixture pressed into a small pellet. Per milligram (or millicurie) of radium such a source may emit about 16,000 neutrons per second. The source must be meticulously encapsulated and sealed to prevent the gaseous decay product radon from escaping. Leakage would be very hazardous and it would also make the source useless, since the needed alpha particles come in part from the disintegration of radon and its daughters.

The neutrons emitted by a Ra-Be source are not of uniform energy; their energy varies widely. The average energy is about 4 million electron volt with a few as high as 15 mev. The corresponding speeds are high, of the order of 1,000 miles per second, and the neutrons are called fast neutrons.

When such a fast neutron source is placed in a moist soil the emitted neutrons interact with the surrounding medium. They collide with the nuclei of the soil in a billiard ball fashion, changing direction as a result and losing energy. With the energy losses the speed diminishes until it approaches the speed characteristic for molecules at the prevailing temperature. For neutrons this is about 1.7 miles per second and the energy is then about 0.03 ev (electron volt). Such neutrons are called thermal, or slow, neutrons. The slow neutrons are finally absorbed by the other nuclei, and thus their existence ends. In a material containing appreciable hydrogen, a neutron, after the first collision with a hydrogen nucleus, is not likely to travel much farther. Consequently, if the neutron source is enclosed in a material that is rich in hydrogen, it will be enveloped in a dense, spherical cloud of slow neutrons. The density of this cloud represents an equilibrium between the rate of thermalization and absorption by the medium and the rate of production by the source. This equilibrium is reached very rapidly after insertion of a source, as a matter of a fraction of a microsecond (one millionth of a second). If the medium surrounding the source contains less hydrogen, the cloud of slow neutrons will be less dense and extend farther from the source. This is so because a fast neutron has to travel farther, on the average, to encounter a hydrogen nucleus and start becoming or continue being thermalized. Thus, the measurement of soil moisture by the neutron method is essentially a measurement of the density of the slow neutron cloud developing when the Ra-Be source is inserted into the soil.

Although the above description is not quantitative, it shows that the density of the slow neutrons around the source is determined by the concentration of the hydrogen nuclei in the medium. Assuming that the only hydrogen nuclei are those in the soil water, we may say that the density of the slow neutrons is a measure of the moisture content by volume.

The question remains as to how the neutron density is to be determined. Various types of slow neutron counters exist, but the more commonly used types are proportional counters filled with enriched BF_3 gas or lined with enriched metallic B. The term "enriched" means that a higher proportion of the B^{10} isotope is present than in natural boron, which consists of 18% B^{10} and 82% B^{11}. Boron^{10} is highly effective in absorbing slow neutrons and in so doing emits an alpha particle which sets off the counter and produces an electrical pulse.

It may be evident from the foregoing that the counter must be of a certain size in order to be most efficient. First of all, it should be as close to the source as possible. The fast neutrons and the gamma rays that are emitted by the source do not interfere with the counting of the slow neutrons, if the counter is operated properly. Second, the counter should be inside the volume of soil within which the slow neutron density varies with the moisture content. It was shown by Van Bavel, Underwood, and Swanson (13) that this means a sphere of about 6 inches radius around the source. Third, the counter should be as large as possible so it will count as many slow neutrons as possible and accordingly be more accurate. Fourth, the presence of the counter should not interfere with the nature of the medium.

Obviously, all these requirements cannot be met fully; some compromise must be reached. The design, which is discussed in more detail on page 6, appears to give a satisfactory middle road. It is schematically given in Figure 1. The construction of the counter makes it impossible to place the source closer to the counter. The source itself is surrounded with lead to reduce the gamma hazard.

The BF_3 counter is held at a certain, suitable voltage; and the pulse produced by each neutron as it is counted appears as a slight, temporary dip in the counter voltage. These dips are from 1 to 5 millivolts in size and last for a small fraction of a microsecond. The counter can therefore count many pulses per second without showing so-called coincidence loss. In actual practice, counting rates are rarely more than 500 counts per second, far below the rated capacity of the counter. Each count represents the elimination of a B^{10} atom contained in the counter, but the number of B^{10} atoms in the counter is so large that the device can be used for many years. Actually, the inert gas which is also in the counter will be depleted by ionization long before the B^{10} is used up.

The counter pulses are very small and must be amplified before they can be counted by a suitable mechanism. This can be done by various forms of portable equipment. (See p. 9)

This is only a brief account of the physical principles of the neutron scattering method for measuring soil moisture content. It is well to point out, however, that in spite of a relatively simple sounding description it is difficult to predict mathematically the relation-

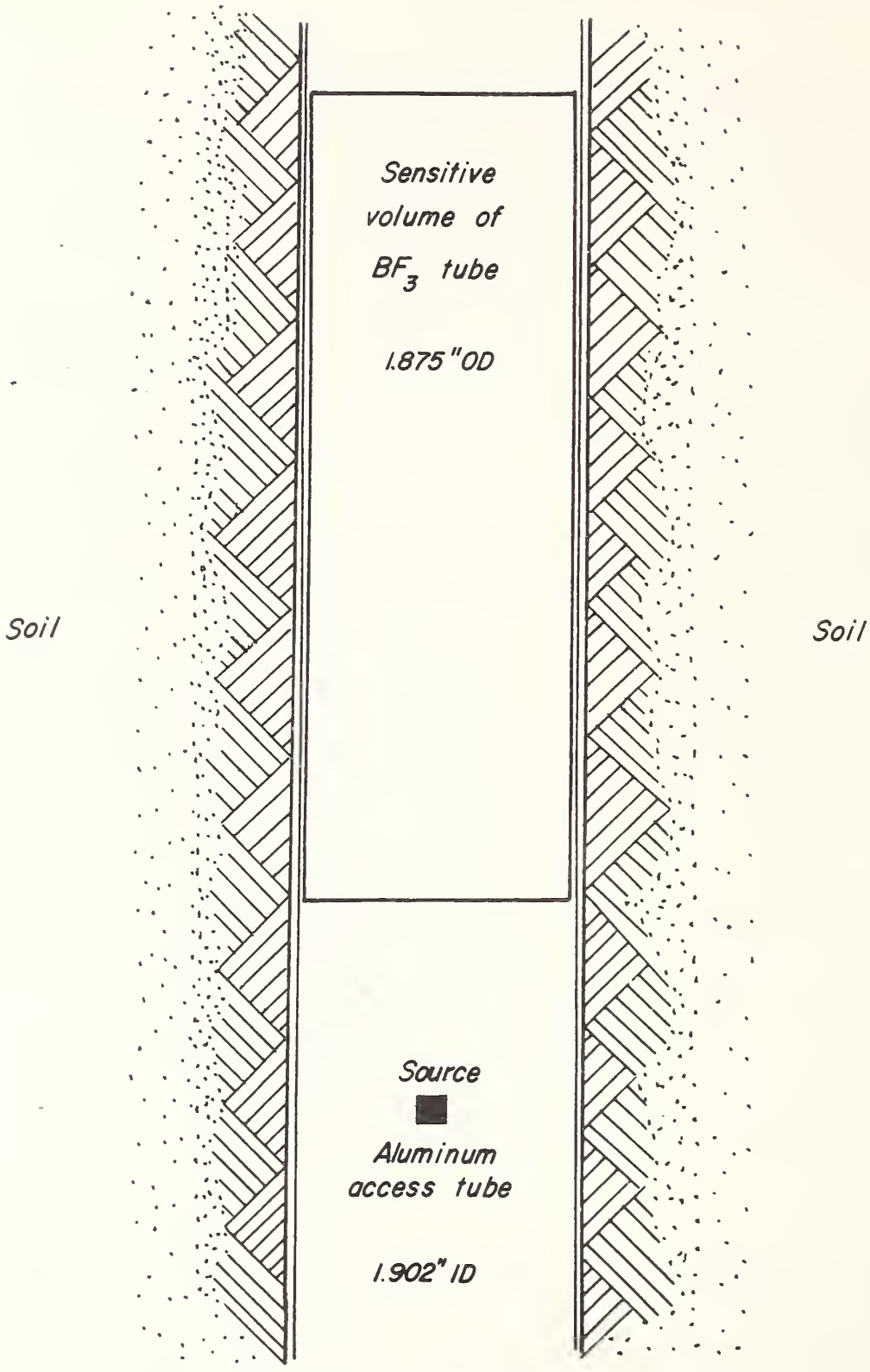

Figure 1. Schematic drawing showing the relationship of source and counter in the neutron moisture probe. The probe is shown in the access tube.

ship between slow neutron counting rate and moisture content. In practice, the source and counter must be inserted in the soil by means of a cylindrical access hole. This complicates the geometry of the problem. Furthermore, even in the ideal, spherical geometry the mathematics is difficult. Therefore, the calibration of neutron moisture probes will have to be obtained from measurements on standard soil samples or equivalent media. Holmes (4) has given results of a theoretical approach to the calibration problem.

EQUIPMENT

Fast Neutron Source

Although a number of fast neutron sources are known and readily available, the use of a Ra-Be source is the most practical choice for the following reasons.

a. The half life is long (1,620 years) and correction for decay is, therefore, not necessary.

b. Ra-Be sources are readily available and small sources are not expensive (about $200).

c. Radium is an energetic gamma emitter. This may seem a disadvantage; but, actually, the gamma radiation does not interfere with the measurement. From a health physics viewpoint the gamma radiation serves as a warning, detectable by common devices, of the presence of the less evident but potentially dangerous fast neutron emission. For each fast neutron emitted a Ra-Be source undergoes about 2,000 disintegrations. Several times this number of high-energy gammas are produced by the radium and its daughters. If, therefore, the gamma radiation intensity and the associated exposure is held below permissible levels, the neutron exposure can also be regarded as permissible. The health hazard problem is further discussed on page 22.

Radium-Beryllium sources, as now sold in North America, are cylinrical, stainless steel capsules, doubly sealed with hard solder. The dimensions depend upon the source strength, but for the present method length and diameter are limited to between 1/2 to 3/4 inch.

The strength of the source to be used is an important item. It is obviously desirable to hold the activity down as low as possible. Low activity means lower cost; above all, it means lower health hazard.

From data which are supplied (p.21) it may be shown that present probe design of 2-millicurie strength should be satisfactory for most work. Speaking generally, a 2-mc source is quite small. Without any

shielding whatever, the gamma radiation level around such a source is 17 milliroentgen per hour at a distance of 1 foot and 4 mr per hour at a distance of 2 feet. The corresponding fast neutron flux is 1 n sec^{-1} cm^{-2} and 0.25 n $sec^{-1}cm^{-2}$ (n = neutrons), respectively. The gamma hazard is by far the greater one.

Nevertheless, a 2-mc source should be used in such a manner that the exposure is at a minimum. This can, in part, be achieved by shielding the source with lead, insofar as compatible with the probe design. The manner by which this is done is shown in Figure 2, which is the actual probe design recommended in this report. It may be seen that about 0.8 inch of lead is provided around the side and at the bottom. Thereby, the gamma radiation level in these directions is reduced to 6 mr per hour at 1 foot and 1.5 mr at 2 feet. The lead shielding does not reduce the fast neutron flux because lead is practically transparent for fast neutrons.

It is advisable to store a 2 mc Ra-Be source, when not used, in a more effective shield. This depository should be large. It can most cheaply be made of brick, sand, or a similar material. Provision of a 1-foot layer of sand around a 2-mc source will reduce the gamma and neutron radiation level to far below permissible values at the periphery of such a container. This limit is now the equivalent of 5 mrem per hour (see Dose in Glossary, p.ii). A suggested simple design for a permanent depository is given in Figure 3.

Detector of Slow Neutrons

The slow neutron detector which is suggested here is shown in Figure 2. It consists of three parts, which form one unit. The whole unit has an outside dimension of 1.875 inches diameter and fits easily into the access tubing which this report recommends. A rather close fit is important to obtain the highest possible counting rate for a given source strength.

The unit is made of brass. The bottom part is a cap, filled with lead, which attaches to the center part by means of a shoulder and collar and three screws. In the lead a cylindrical well is provided which accomodates the source capsule, bringing the capsule as close to the counter bottom as possible. The middle part is the counter itself. This is a 5 1/2 inch long brass cylinder provided with a central wire, mounted on insulators. The cylinder is filled with enriched BF_3 gas at a pressure of 20 cm Hg. The center wire is held at a potential of about 1400 volts. Those slow neutrons which are counted give pulses at the counter terminal of around -1 to -4 millivolt. The size of gamma-induced pulses is only a fraction of that of the neutron pulses.

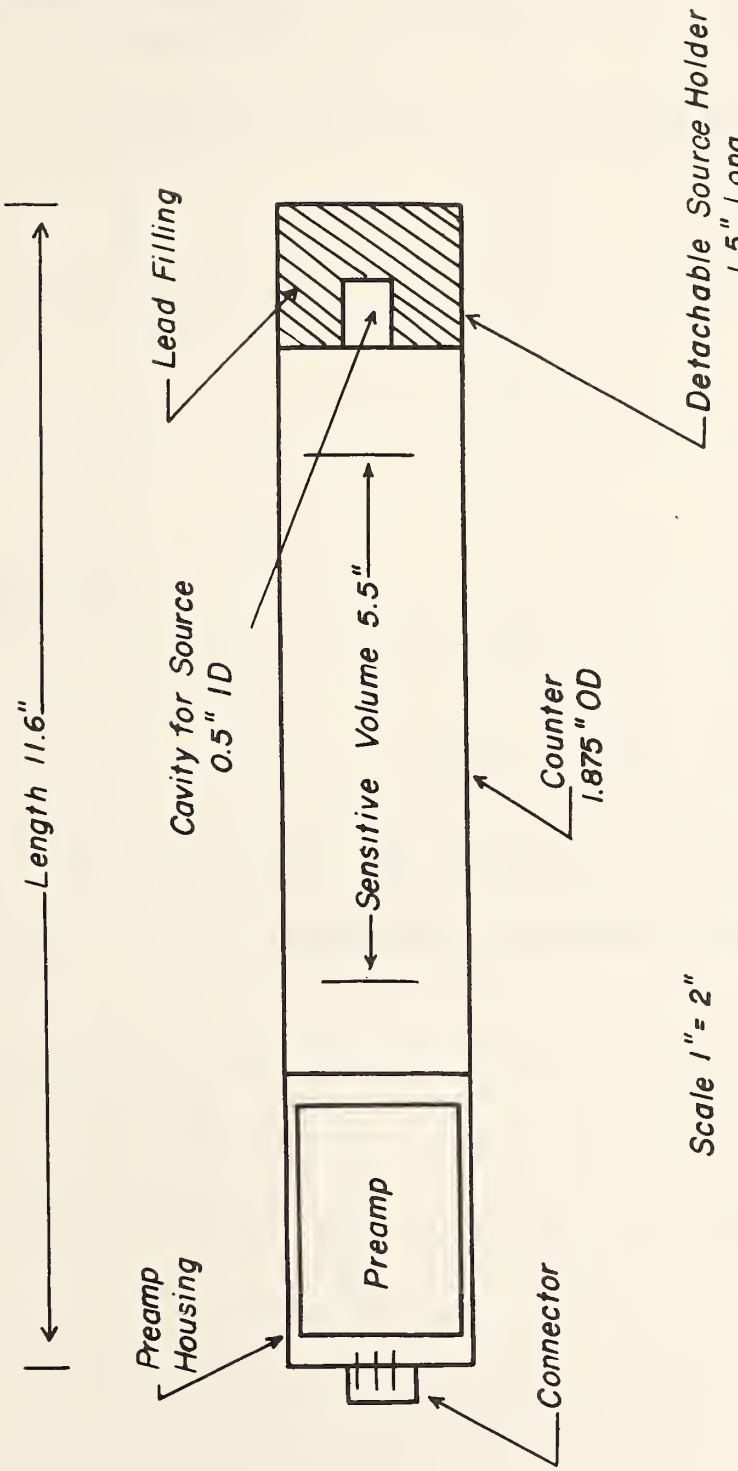

Figure 2. Schematic drawing of slow neutron moisture probe.

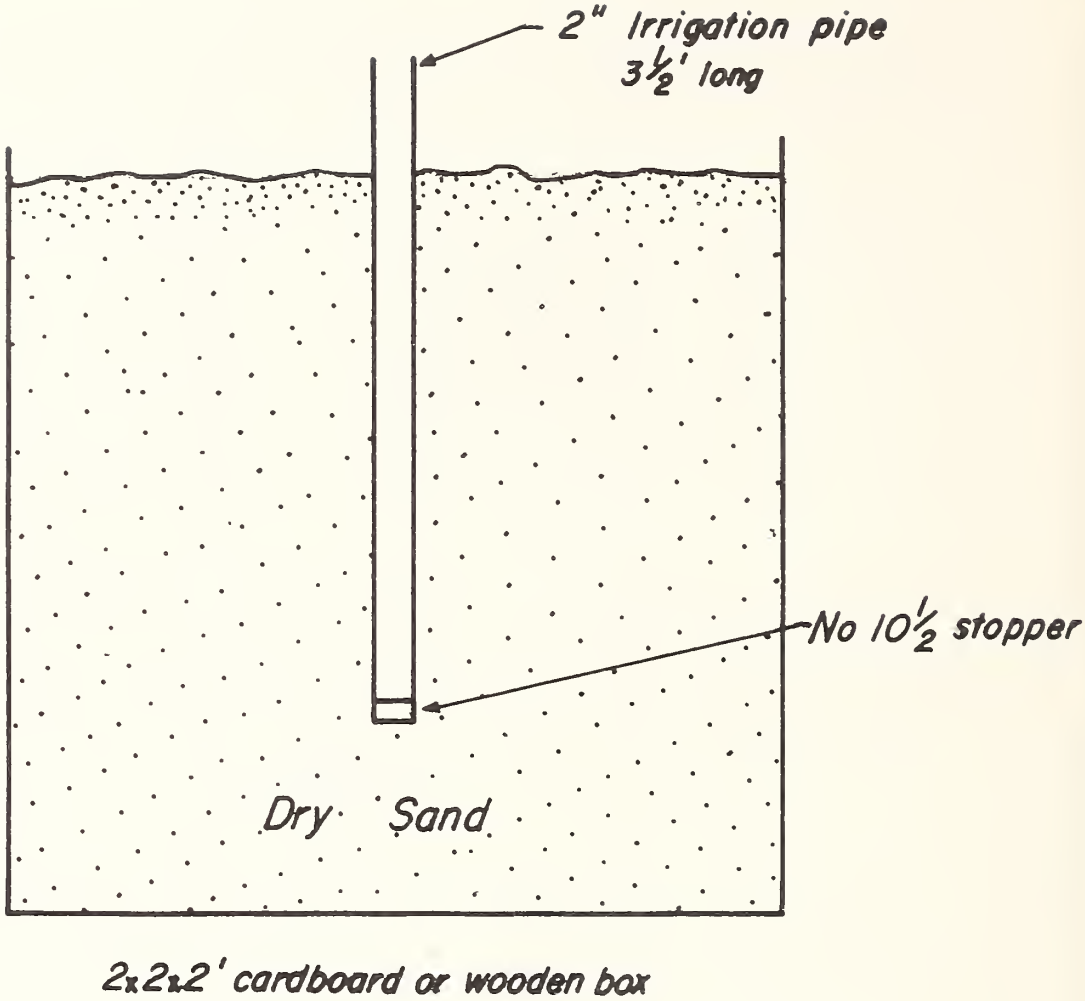

Figure 3. Simple design for a storage facility for neutron moisture probe.

Because the conveyance of such small pulses to a counting device over appreciable distances is not simple and may give practical complications, the detector contains an amplifying device. This is the third, or top, part of the detector. A three transistor amplifier is mounted above the counter. It amplifies the pulses about 80 times and makes it possible to use fairly long cables to the detector without trouble.

At the top of the detector there is a double connector. One contact supplies the high voltage (1,400 V) to the counter and also carries the signal (neutron pulses) to the counting device. The other one provides a 10-v potential to the amplifier.

The entire detector is light enough to be carried by its own cable, which is clamped securely to the body. Dimensions of the detector are given in Figure 2.

Counting Device (Scaler)

The density of slow neutrons in the soil and in the counting tube is evident in the form of a given counting rate. This counting rate may be determined by a rate meter or by a scaler. The first indicates the count rate directly and the second registers the total number of counts over a given time period. In either case, identical results are obtained. Practical experience has demonstrated that of equipment commercially available, best results will be obtained by using a portable scaler. This scaler provides a stable high voltage for the counting tube, and it registers the number of counts that occurred during a pre-set amount of time. The scaler is battery or line operated; the battery may be recharged with a built-in charger. Technical details on the scaler are made available by the supplier. Several points should be raised here, however.

The reproducibility of the timer should be checked very thoroughly. In most work it will be sufficient to take 1 minute counts. The proper position of the stop on the timer should be ascertained with a good stopwatch. After setting, repeated runs should be made to check the reproducibility. Deviations of more than half a second per minute should not be tolerated.

The setting of the high voltage control and of the input sensitivity control are both very important for correct operation. Once these settings have been determined they should be left that way. This can best be explained by referring to Figure 4, which shows in the solid line how, for a given tube voltage, the counting rate depends upon input sensitivity. At low input sensitivity the counting device counts not only the slow neutrons but also gammas and amplifier noise. The contribution of the last two categories is shown in the interrupted

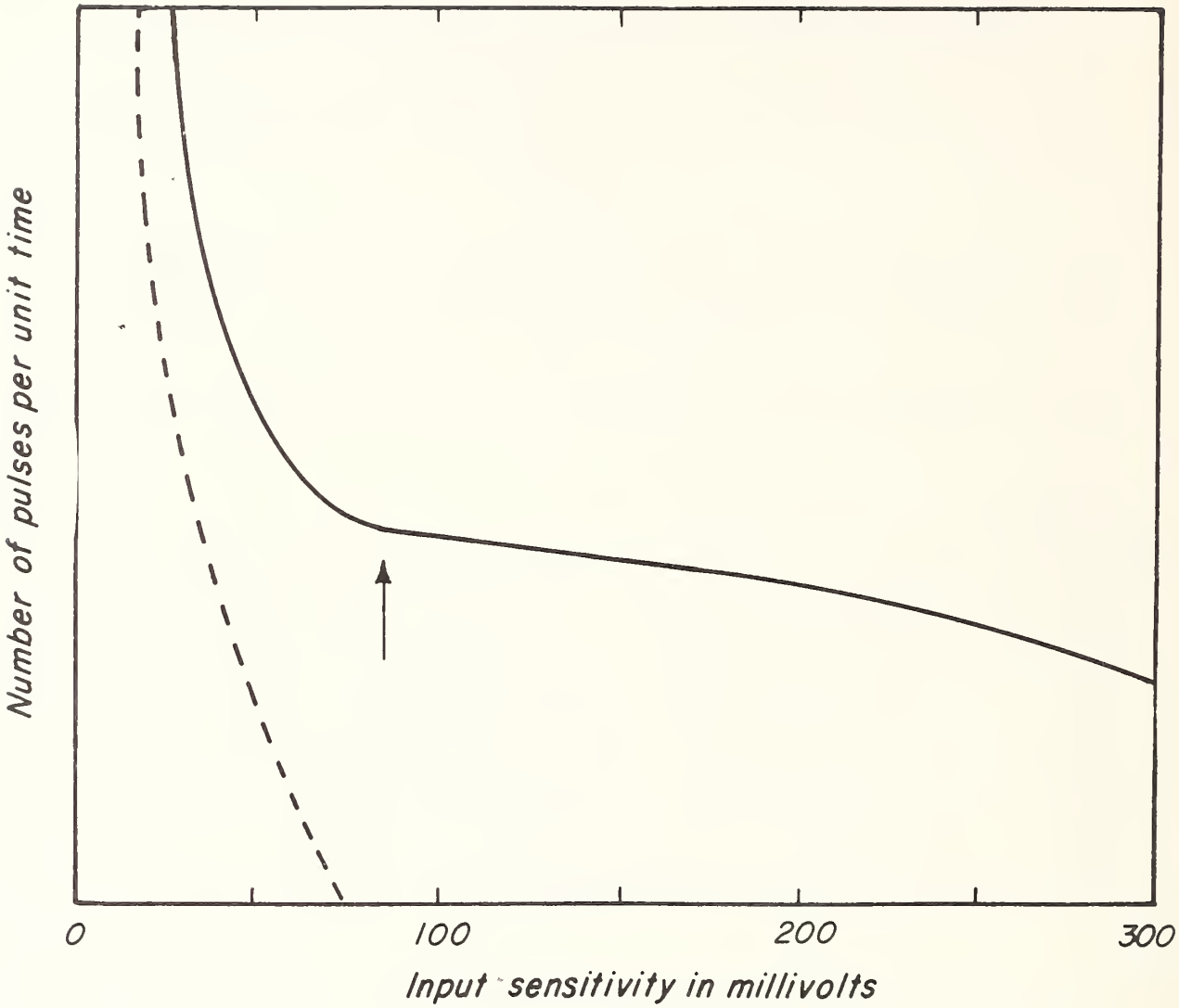

Figure 4. Counting rate of neutron moisture probe as determined by input sensitivity of counting device. Solid line refers to a probe inserted in moist soil and the interrupted line to a probe suspended in air. Background is neglected. The arrow indicates the optimum input sensitivity.

line. In order to exclude these pulses the input sensitivity should be set at a level as indicated by the arrow in Figure 4. It is obvious why this setting should not be changed thereafter.

Changing the tube voltage will change the form of the curve in Figure 4. Generally speaking, an increase in tube voltage will shift the entire curve to the right and vice versa. Therefore the tube voltage should also remain the same.

The procedure for determining the correct adjustments is as follows. First, adjust the high voltage control (on top of the scaler) to obtain a voltage of 1,400 V, as indicated by the dial. After this has been done, lock the adjustment screw.

Connect the detector, placed on a table, to the scaler. Unscrew the panel of the scaler and lift it out and place it so that the sensitivity control can be adjusted with the multiple cable connected. One should be careful not to shorten any part of the circuit and not to receive a shock in handling.

Turn on the scaler, then turn on the counting switch. With the "test" circuit check that the scaler is operating properly. In the "use" position there should be no appreciable count rate; there should be less than 150 counts per minute.

Turn the sensitivity control clockwise until the count rate starts increasing. Then counter-clockwise, enough to exclude the gamma and other pulses not caused by slow neutrons.

Next, the detector is placed in the full calibration bucket (see next section). A count rate of approximately 8,000 cpm should be obtained. If this test is satisfactory, the scaler can be closed up and neither the sensitivity control nor the high voltage control will need further adjustment.

It is possible that even in extreme clockwise position, the count rate does not become appreciable. In that case one merely backs the control slightly from the extreme position.

Maintenance instructions for the scaler are supplied by the manufacturer.

Calibration or Standard Bucket

This is a device to insure proper operation of the equipment and to compensate for small changes in operating characteristics. The standard bucket is fabricated from an ordinary 12-quart galvanized steel

bucket. A 2-inch central tube is made from 22-gage galvanized steel stock and a cover from the same material. The cover is provided with 2 holes, 1/2 inch in diameter, closed by rubber stoppers. These holes are for filling and emptying the bucket.

Dimensions are shown in Figure 5. Care should be taken that all solder joints are watertight.

Access Tubes

The insertion of the detector in the soil is not practical without using some kind of access tube. The choice of tube is important. The material must not interfere with the measurement, nor corrode, it must be inexpensive, and must be generally available. By far the best choice is common 2-inch aluminum irrigation pipe. This material can be bought wholesale for 20¢ to 25¢ per foot. It is made of a relatively hard aluminum alloy that is cut easily with a hack saw; it is made to close tolerances. The outside diameter is 2.000 inches and the inside diameter 1.902 inches.

Aluminum is practically transparent for fast and slow neutrons and does not corrode seriously. Tubes, once installed, may give years of service.

The installation of the tubes is greatly facilitated by two accessories. One is a piece of cold rolled steel tubing of identical dimensions; the other is a 1 3/4-inch auger, welded to 1/2-inch steel tubing provided with a handle. By augering out the hole and pushing the steel tube down alternately, the required hole is easily made even in difficult situations. Then, the aluminum access tube can be set in its place. The tubes may stick 2 to 4 inches out of the ground. It is not necessary to cap them.

It is important that the access tubes not be bent or nicked by rough handling, because the detector fits very closely and the least deviation from true size will result in difficulty.

Cable

A 20-foot electric cable connects detector and scaler. All possible care should be exercised to keep the connectors free of dirt and moisture. Also, be careful to prevent undue strain on the joint of cable to connector, for pulling or twisting is likely to give poor connections. In practice, most trouble is traceable to a faulty cable. In case of failure, this aspect should be investigated first.

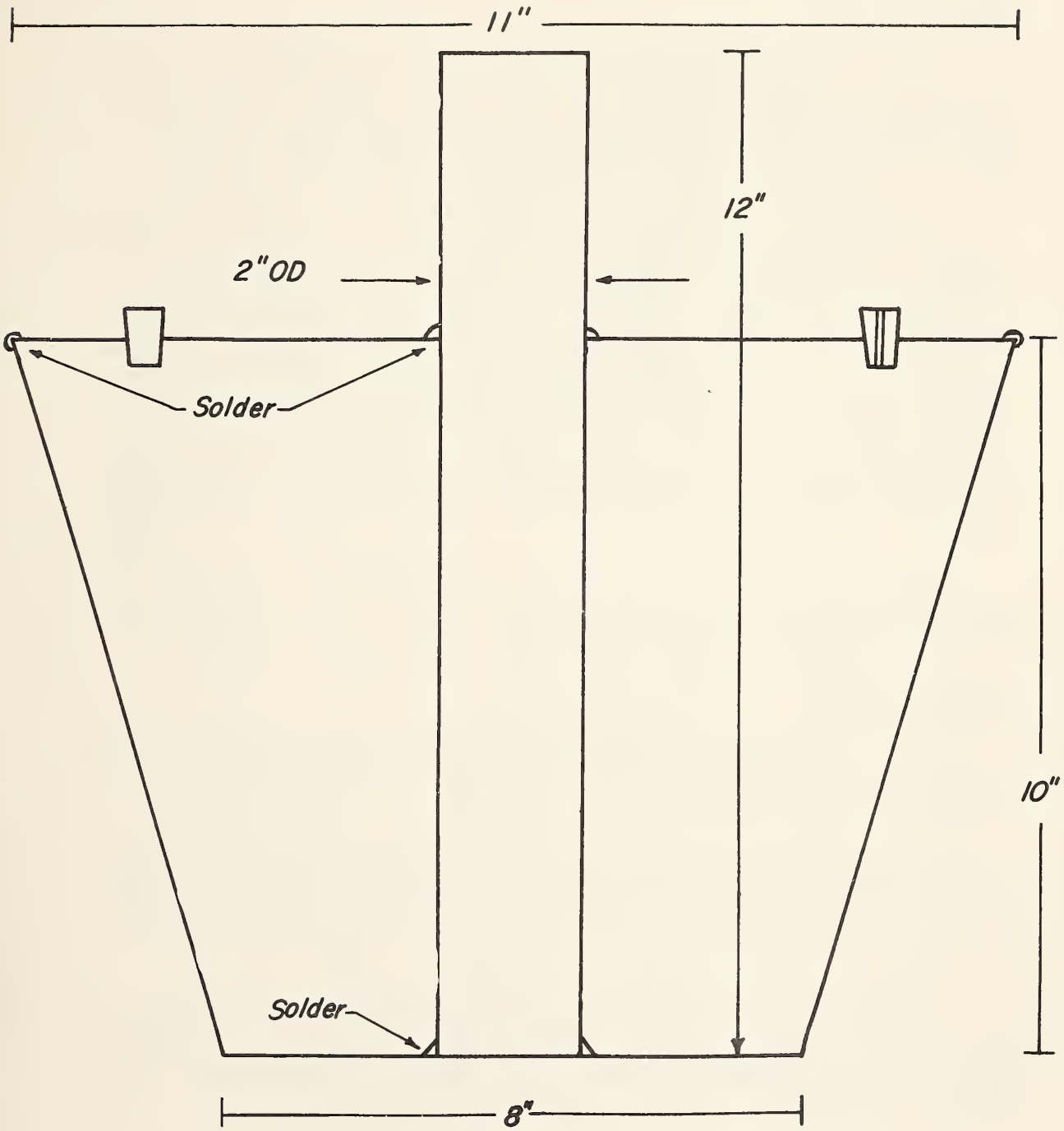

Figure 5. Construction drawing of standard bucket.

OPERATION

Depth Adjustment

The neutron probe must be inserted in the access tube and held at the desired depth. Holding the probe may be done by various means but a simple and effective method is to use an ordinary clothespin. Masking tape, colored cloth adhesive tape, surgical tape, or metal bands may be used to indicate 12 or 6 inch intervals on the cable.

However, before marking the cable one must know what the reference depth is and, also, how much the access tubes are protruding from the surface. The reference depth can be found by a relatively simple experiment, illustrated in Figure 6. The probe was lowered inch by inch into an access hole in a layered soil. This soil consisted of 16 inches of coarse sand, then 4 inches of a fine sandy loam, and then again 16 inches of coarse sand. After wetting to excess, a moisture distribution of about 5-25-5 percent by volume was obtained. When the readings with the probe are plotted against the depth of an arbitrary reference mark, for example, the top of the probe, it becomes clear which the "true" reference mark should be. In the case of the probes described in this report, this is a point 8 inches below the top of the probe.

If the access tubes are protruding 4 inches from the surface, the mark for the 1 foot depth should be made 12-8+4 = 8 inches above the top of the probe, and so on.

Standardization

In order to insure the proper operation of the equipment and to eliminate the effects of any small variations in performance, the probe and scaler should be standardized before and during measurements.

The procedure is as follows. Connect scaler and probe and verify, by means of the "test" position, if the scaler is working. Also, check the battery condition. Lay the probe in the lid of the scaler and count for 1 minute. The "background" count thus obtained should not be much more than 100 counts per minute.

Then, the probe is placed in the standard bucket (see Figure 5). For the most accurate work the bucket should sit on dry soil, on a small box, or, when possible, in a car or truck. This is to avoid any effect on the standard count of moisture underneath the bucket. The effect, if any, is small, but it is best avoided.

As said before, the count rate will be around 8,000 cpm. However, this will vary from one set of equipment to the next. Successive 1-minute counts are taken until identical numbers are obtained. Of

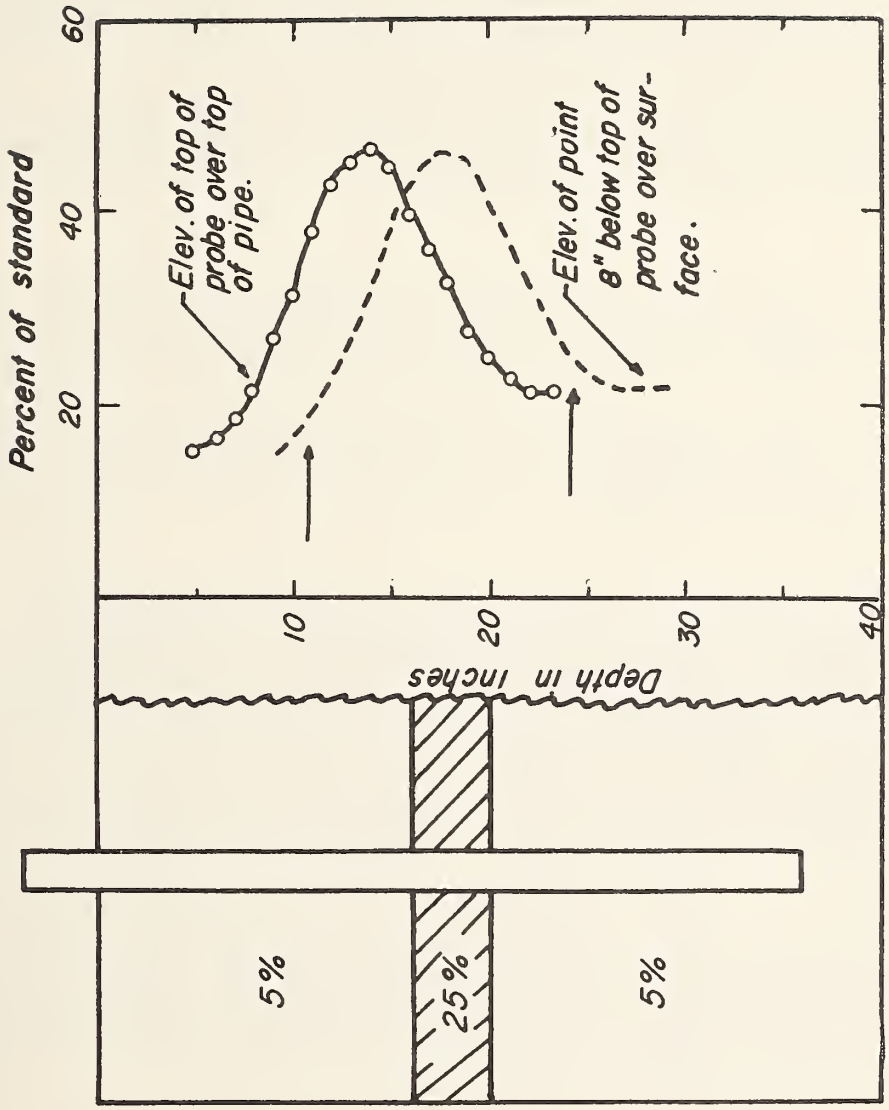

Figure 6. Counting rate of soil moisture probe as affected by a 4-inch discontinuity in an otherwise homogeneous soil.

course, one should realize that the count rate has an innate, statistical error. The standard error is about 100 cpm. A good rule of thumb is to accept results as identical when they differ by no more than 200 cpm (30-percent level of probability). Often, a 5- to 10-minute warm-up time is necessary before the standard count settles down to a constant figure.

As measurements are being taken, the standard count is determined again from time to time. The frequency can depend upon convenience, plot layout, and experience. A suggested rule is to take a standard count every ten readings, but this may be too frequent to be convenient.

It is helpful if standard counts are taken in a vehicle, so as to obviate carrying the bucket. Experience and the need for accuracy will soon enough suggest the best procedure.

Measurements

The actual measurements do not require particular comment at this time. A discussion of the nature of the results is given in the next section.

For most work it seems sufficient to take 1-minute counts. Generally, this will give a standard error of an individual reading of about 0.5 percent moisture by volume. For greater precision the reading time could be increased to 2 minutes.

The following applies to the depth of reading. Approximately speaking (see also next section), a 6-inch layer is characterized by a single measurement. It is inadvisable, however, to measure closer than 7 inches to the surface. Therefore, a sensible measuring scheme would be: 7-13-19-25-etc. inches, resulting in data for 4-10, 10-16, 16-22, 22-28 inch layers, etc. Information on the top layer may be obtained by merely laying the detector on the surface. This is a much less precise measurement, owing to the roughness of the surface and inhomogeneity of the upper soil layers, and requires a separate calibration.

No information is available on the required number of replicate installations that are needed for the characterization of a given area. Investigation of this point is needed. All that appears certain now is that the sampling error of the neutron method should be much smaller than that of any other type of measurement.

RESOLUTION, CALIBRATION, AND PRECISION

Resolution

The question of the size, in particular the thickness, of the sample characterized has been mentioned before. The exact determination of the area of measurement required careful experimentation, such as that reported in references 12 and 13. However, a sufficiently accurate idea can be obtained from Figure 6. When the readings are plotted against the depth of the probe reference point (interrupted line) it may be seen that the reference point can approach to within about 4 inches from the bottom and 5 inches from the top, before the layer of higher moisture content is detected. This indicates a resolution of 9 inches. Actually, the effect at a distance of 3 inches on either side is small and the 6-inch figure mentioned before is arrived at in this way.

When therefore, successive 6-inch measurements are taken, the entire profile is measured with a small amount of overlap. The situation is somewhat different in regard to the surface of the soil. This represents a very marked discontinuity and its influence extends deeper than 5 inches as demonstrated in Figure 7. Apparently 7 inches is the first depth at which there will be no interference from the surface.

Calibration

It is very important to realize that the potential precision of the neutron method is greater than that of any other method under field conditions. It is an error to believe that the method should be calibrated in the field or "verified" under field conditions. Calibration should be carried out with large, homogeneous masses of soil of which the density and moisture content are accurately known.

A series of such standards, 48 x 48 inches in surface area and 36 inches deep, has been constructed at Raleigh and is the basis for all calibration at this location. The nine standards cover a range in moisture content from 5 to 42 percent by volume. The density has been determined for successive 3-inch layers to the nearest 0.01 g cm^{-3} and the moisture content also in 3-inch layers to the nearest 0.2 percent by weight. Since the density runs around 1.4 g cm^{-3} the moisture content by volume is known to at least the nearest 0.5 percent by volume.

By counting for a sufficiently long time, the counting error can be eliminated for practical purposes; then the calibration is limited in precision by the uncertainty in the determination of density and moisture content. A final, direct calibration was made in September 1957 at Raleigh with a certain set of equipment which will remain unchanged. This calibration curve is shown in Figure 8. All later curves were derived from

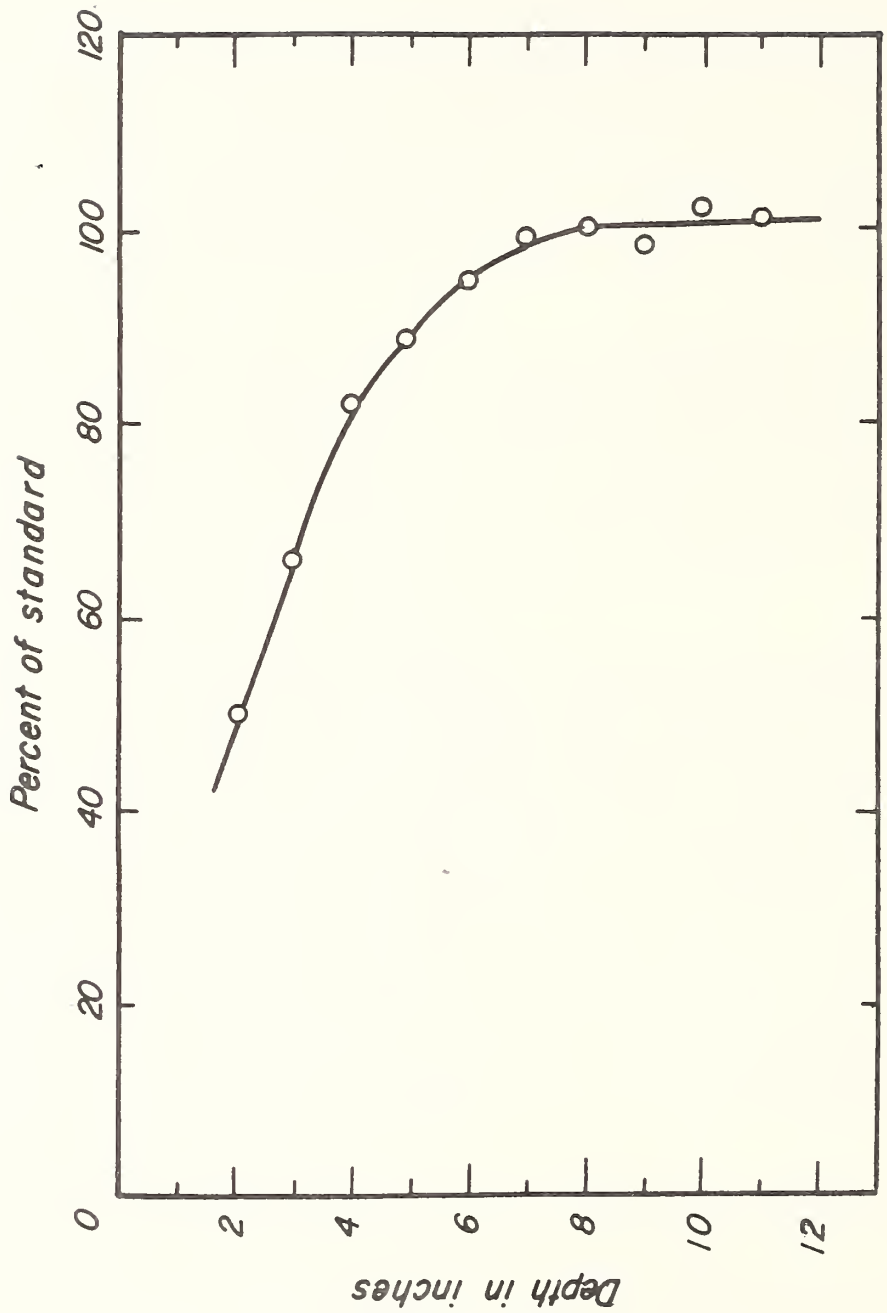

Figure 7. Counting rate of soil moisture probe as affected by depth of insertion in soil of about 45 percent moisture content by volume.

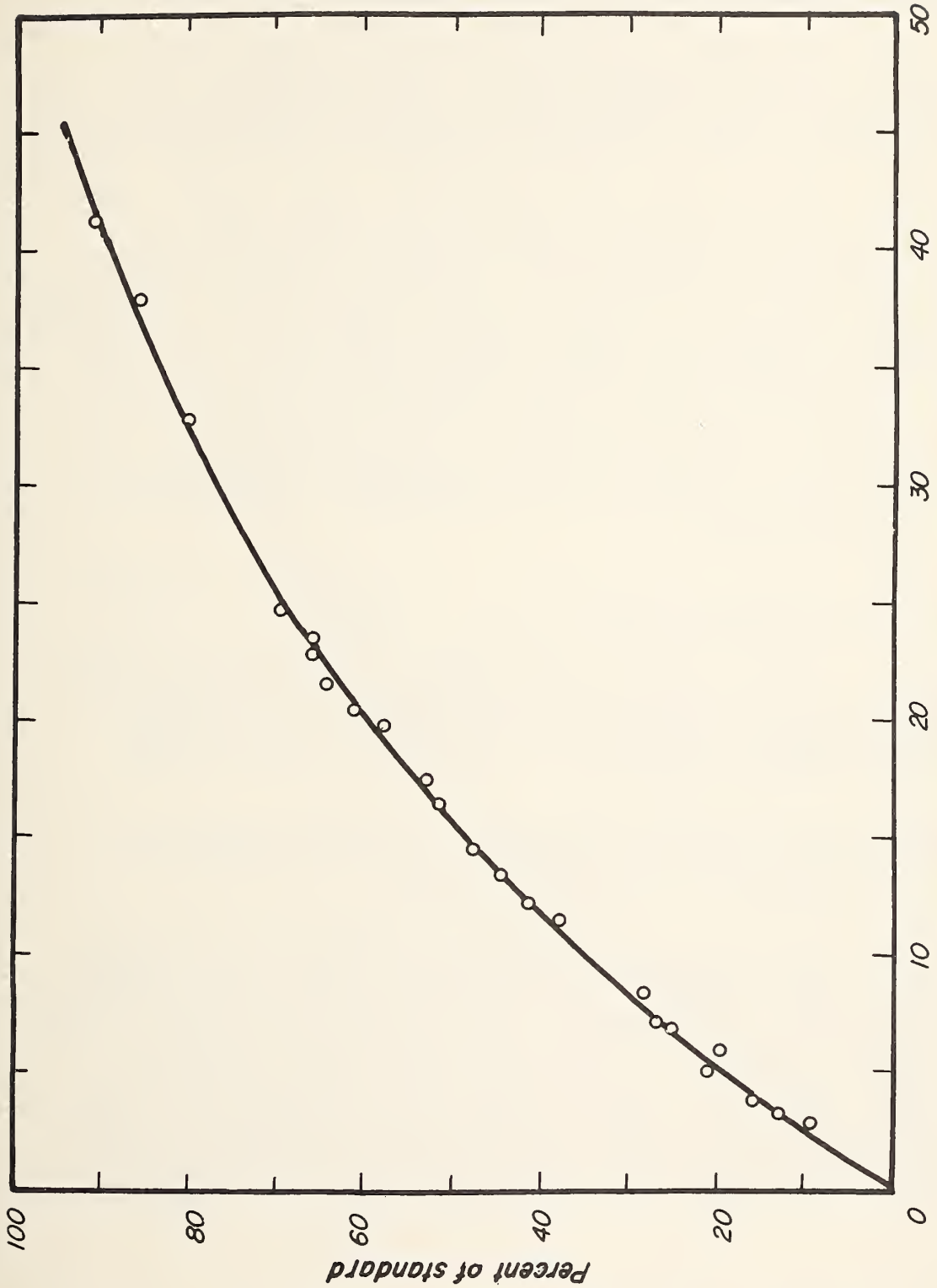

Figure 8. Calibration of standard neutron moisture probe (1A-10mc-2800E10).

the one in Figure 8 by making measurements with the standard equipment and with any equipment which was to be calibrated.

A calibration curve, thus obtained, is shown in Figure 9 for a probe such as is shown in Figures 1 and 2. The expectation is that all probes patterned after this one and used with a standard bucket such as is shown in Figure 5 will give very similar, if not identical, calibration curves, even with slightly differing source strengths.

It will be noticed that the calibration in Figure 9 shows a slight flattening at the higher moisture content. (The highest value is approximately that of saturated sand.) Positioning the source midway the counter, it is true, improves the situation. This is demonstrated in Figure 10, wherein the curve of Figure 9 is compared with one obtained in an identical access hole by means of a probe which had a 1 1/2-inch diameter counter instead of a 2-inch one and a source attached to the counter, midway of the sensitive volume, instead of at the end. The resulting response curve is more linear, but the advantage seems slight in view of the more complicated arrangement. The overall counting rate is decreased as a result of the side arrangement. Per millicurie Ra-Be, we have in soil with a moisture content of 25 percent the following counting rates:

With 2-inch detector, source at end- - - - - 3,550 counts per minute
" 1 1/2-inch detector, source at side - - 2,800 " " "

Therefore, we conclude that the end arrangement gives greater efficiency of counting and also a better shielding arrangement, at the expense of some linearity in the calibration curve. It appears that the lesser health hazard implied by the use of a 2-inch probe is more important than the effect on the calibration.

Experiments not reported here also have shown that resolution is not greatly affected by positioning the source at the middle of the counter as contrasted with having it at the end.

An important aspect of the calibration is whether it is the same for all soils. The standards at Raleigh consist of sand, very fine sand, kaolinitic and high sesquoxide subsoil clay, and silt - - all at different moisture content. The standards seem to lie all on one curve. Gardner and Kirkham (2) showed no differentiation between soils. Knight and Wright (5) demonstrated that organic matter did not cause deviation from the universal relationship. However, there are indications that in some cases deviations from the general rule may occur. Discrepancies that have come to the attention of the author all concern fine textured soils, and some connection with the nature of the clay fraction is indicated.

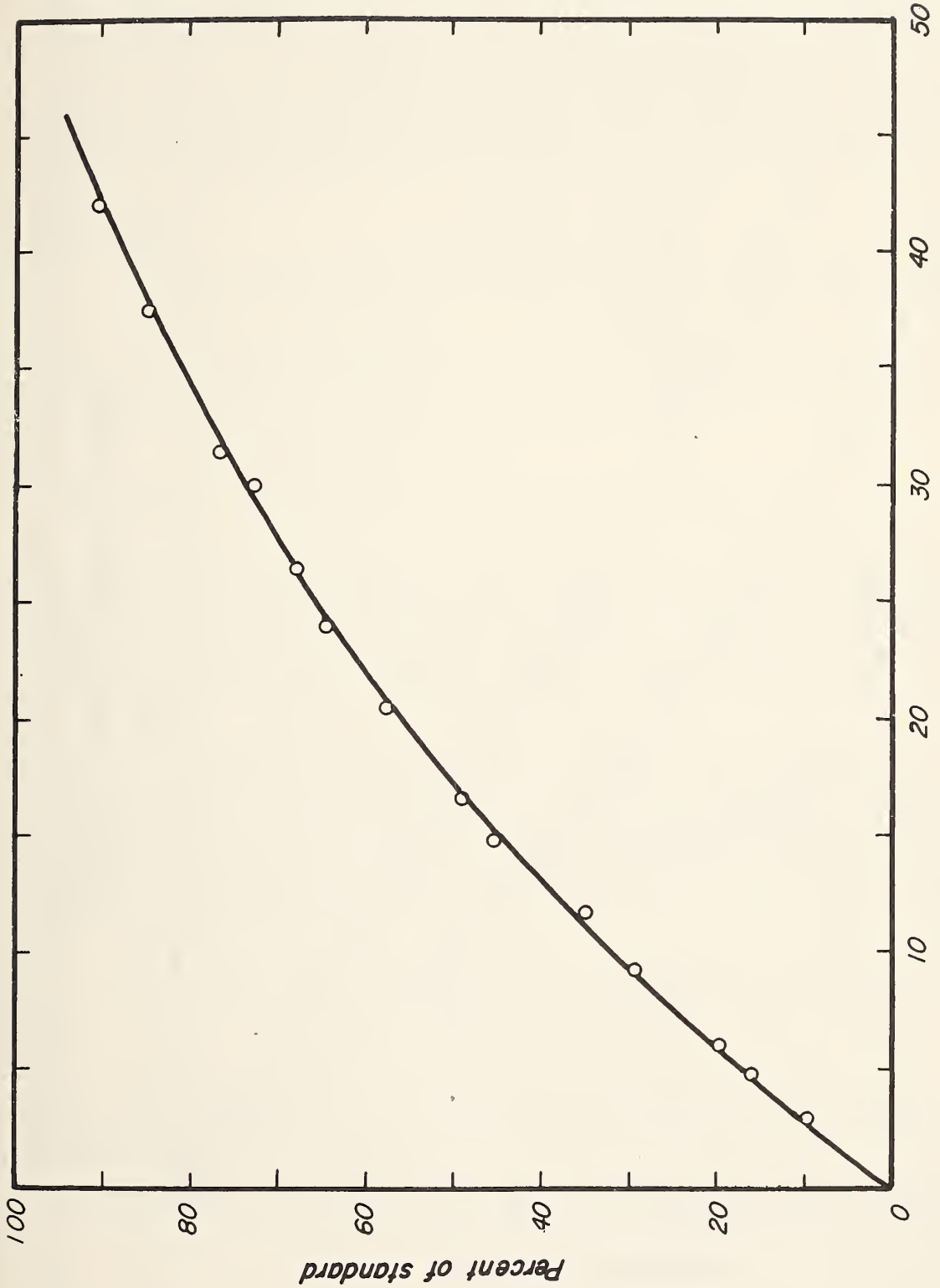

Figure 9. Typical calibration of a 2-inch neutron moisture probe (5A-5mc-2800E10).

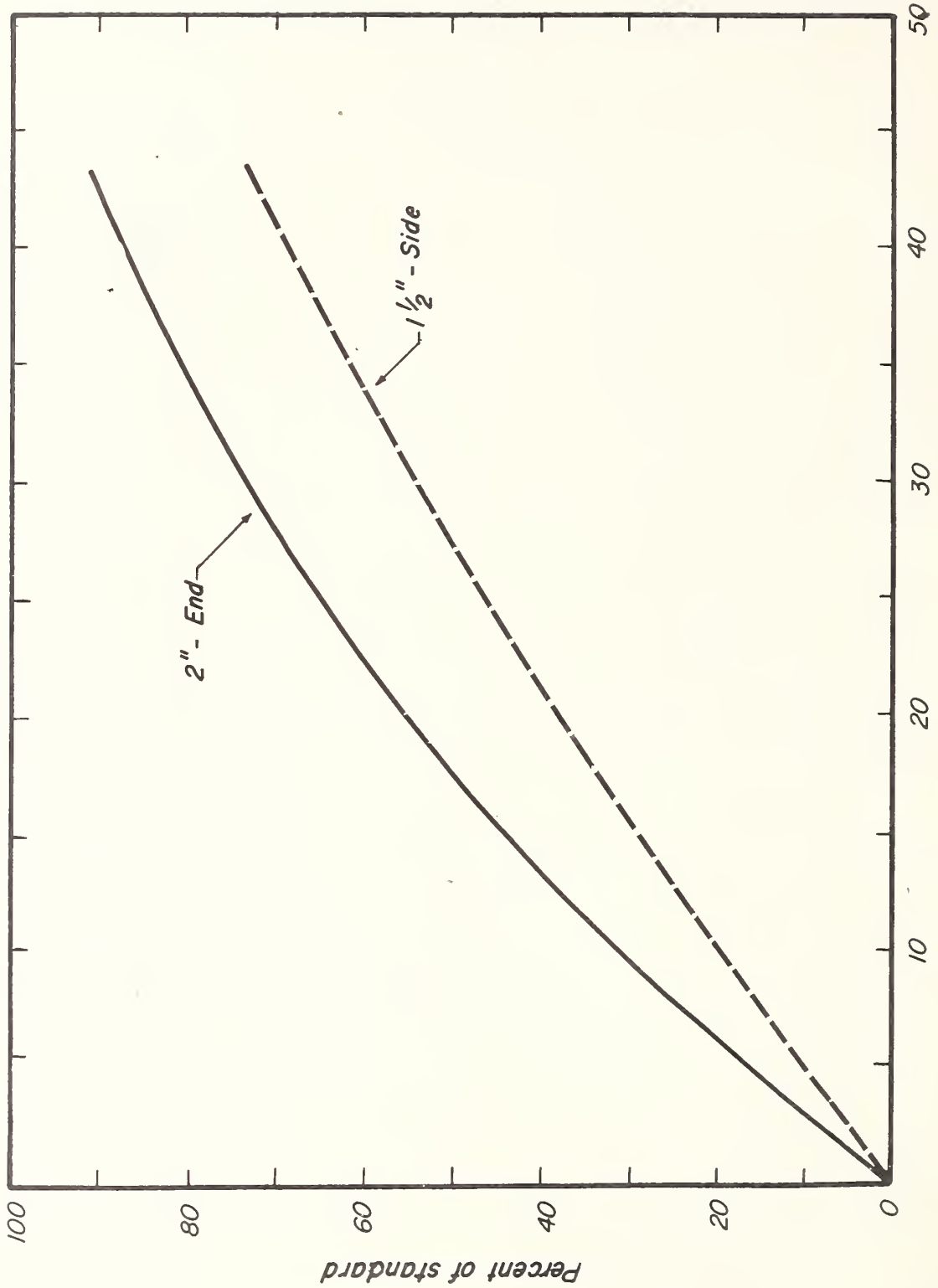

Figure 10. Comparison of calibration of a 2-inch neutron probe with source at the end (solid line) with a 1 1/2 inch neutron probe with source at the center (interrupted line).

The above may serve as a general word of caution in the use of calibration curves. Other than the just-noted deviation, the calibration is unaffected by any physical orchemical properties of the soil, such as density, structure, temperature, acidity, base saturation, or salinity. Hysteresis does not play a part in the moisture-slow neutron density relation. Sensitivity is, in first analysis, the same throughout the range from oven dryness to saturation.

Precision

Various times heretofore the precision of the neutron method has been considered. The matter will now be dealt with more exhaustively.

The moisture content, which is derived from a calibration curve, may be in error, i.e. deviate from the true moisture content in the area sampled, for three reasons. The errors are:

1. Instrument drift
2. Counting error
3. Calibration error (error of prediction)

The first error may result from changes in tube voltage, discriminator level, or amplification. Experience shows that drift is small after initial warm-up. Moreover, the practice of standardization and of reporting results on the basis of the standard reduces the effect of drift to a fraction of 1 percent in terms of counts per minute. It can be safely excluded from further consideration.

Counting error is caused by the irregularity of radioactive decay. It results in a standard error equal to the square root of the total number of counts observed. In calibration procedure a minimum of 10,000 counts is taken and, therefore, a maximum standard error of 1 percent is obtained. However, in making 1-minute counts with the equipment suggested here, and with a 2-millicurie source, the error is larger. Roughly, it is as follows:

At moisture content of 10%, s.e. is 1.7% of counts per minute
" " " " 20%, s.e. is 1.2% " " " "
" " " " 30%, s.e. is 1.1% " " " "
" " " " 40%, s.e. is 1.0% " " " "

These figures can be converted into standard errors in terms of moisture content with aid of a calibration curve such as that shown in Figure 9. The results are:

At moisture content of 10%, s.e. is 0.2% of moisture by volume
" " " " 20%, s.e. is 0.4% " " " "
" " " " 30%, s.e. is 0.5% " " " "
" " " " 40%, s.e. is 0.6% " " " "

The errors listed above can, of course, be reduced by counting for periods longer than 1 minute. If, for example, 2-minute counts are obtained, the errors will be reduced by a factor of $1/\sqrt{2} = 0.7$.

The third and last error stems from the uncertainty in the calibration relationship. As pointed out (p. 17), this uncertainty is primarily caused by sampling error in the determination of the moisture content of the standards and the ensuing error of a value which, in turn, is derived from the use of the calibration curve. We assume, for simplicity, that these two errors are identical. At least they will be of the same order of magnitude.

A study of the calibration data shows that the standard deviation from the curve is about 0.5 percent of moisture by volume and, presumably, this figure will be typical for a value estimated with aid of the calibration curve. This error is fairly well matched with the counting error.

In summary, we may state that with the neutron method as described here the moisture content is determined to the nearest half of 1 percent. Longer counting times than 1 minute will improve the precision, but the improvement will not be great unless the moisture content of the standards were to become more precisely determinable. Anyone familiar with the problems of the mixing and preparing of large samples (2-3 tons) of soil and determining their moisture content will realize that greater precision will be difficult to achieve. Furthermore, it is the opinion of the author that the precision available now will be quite sufficient for most work.

It should perhaps be repeated that increasing the source strength has the same effect as increasing the counting time. The benefit is limited and, in view of the added health hazard, there seems little advantage in having a source greater than 2 millicurie.

HEALTH HAZARD

All radioactive substances are health hazards, no matter how small the quantity, and the exposure should be made as small as possible and practical.

On the other hand, one should not be overly fearful or concerned about working with such materials. A thorough understanding of the hazard and use of adequate and sensible handling procedures will safeguard one against injury.

The health hazard from a 2-millicurie Ra-Be source has already been indicated to some extent. In summary, the moisture probe suggested here has a gamma radiation level of about 6 milliroentgen per hour at a distance of 1 foot. This is equal to 240 milliroentgen per 40-hour

work week, which will result in exposures below the present permissible weekly dose of 300 mrem per week (see Dose in Glossary, p.ii).

It will be clear, moreover, that in ordinary handling the exposure will be much less. Actual records accumulated over 2 years at Raleigh indicate weekly dosages of less than 25 mrem, with frequent use of neutron soil moisture equipment.

Neutron flux was estimated at 1 n $sec^{-1}cm^{-2}$ at a 1-foot distance. This, also, is much below the permissible flux, which is 20 n $sec^{-1}cm^{-2}$ for fast neutrons.

A 2-mc Ra-Be source appears to be a small hazard when used in the prescribed manner. Sensible precautions are:

1. To store the source in an adequate shield (see p.6) and to lock it up when not in use.

2. Not to handle the probe at the source end but at the opposite end.

3. To transport the probe in a safe manner, e.g. on the back seat of the car or in the trunk. (Incidentally, the probe should be handled carefully, and be protected against shock. A small box with excelsior, cotton, or rubber foam placed in the car trunk is a good method for transportation.)

4. To use the standard bucket for carrying the probe in the field. This is practical as well as safe.

5. To label the probe plainly, indicating its radioactive content.

A separate hazard is the possibility of a leak in the source. Manufacturers of radium sources take all precautions to insure a perfect and permanent seal, and leaks are extremely uncommon. However, it is a very good idea to check a Ra-Be source annually with a so-called wipe test. The cavity in which the source normally is contained is wiped with cotton and the radioactivity determined with a regular survey meter (both beta and gamma emission should be checked). This operation is best performed by a competent health and safety officer. If the radioactivity exceeds the background a leak may exist.

Using the indicated procedures and precautions, relatively unspecialized field personnel may use the neutron method for measuring soil moisture with confidence and safety.

GENERAL DISCUSSION AND SUMMARY

Although the neutron method for measuring soil moisture content has many advantages in comparison with other existing methods, it is not without problems.

To some, the initial cost of the apparatus, which may be from $1,500 to $2,000, may be a deterrent. However, if it is remembered that the final result is immediately available after one division and one consultation of a graph or table, the cost per moisture determination is likely to be less than that of any other method. Other methods require laboratory space and facilities, as well as time in making measurements and calculations in the laboratory.

A real disadvantage may be in the limited resolution. For some work it may be necessary to know the moisture distribution by 2- or 3-inch layers, and this cannot be done with the neutron method, judging from our present knowledge.

A practical problem is the fact that in some soils, which shrink appreciably upon drying, the soil mass shrinks away from the access tube, leaving an air space. If this space is in excess of a few millimeters the results will be affected. Furthermore, after rain or irrigation these spaces are likely to fill with water, giving again an abnormal condition. There seems to be no solution except to relocate an access tube around which an air crack has developed.

A further practical problem arises with regard to the calibration. As pointed out earlier, there is every indication that in the majority of soils a single calibration applies and such a calibration can be furnished easily with a probe. This relieves the user from obtaining the calibration himself. However, when there is reason to believe that the general relation does not apply, one has no choice but to determine the calibration himself. Since the construction of the required moisture standards is a rather formidable task, a so-called field calibration is indicated. Its reliability will be no greater than the precision of the moisture determinations that are required in such a case.

The neutron method has been used widely enough to demonstrate its value as a practical field method, but not enough to settle some of the issues raised above. It is hoped that soon more field experience will be available.

A summary of the principal characteristics of the neutron method as described here is as follows:

1. Apparatus consists of a battery operated, portable scaler, a probe, a connecting cable, and a standard. All except the latter are commercially available.

2. The probe consists of a 2-mc Ra-Be source shielded by 0.8 inch of lead, a boron trifluoride slow neutron counter, and a preamplifier.

3. The probe dimensions are 12 x 1.875 inches O.D.made to give a close fit in access tubes made of 2-inch irrigation tubing.

4. With 1-minute counting time the moisture content is determined to the nearest 0.5 percent of moisture by volume.

5. The calibration curve is almost linear up to moisture contents of 40 percent. A single curve appears to be valid for many soils, although the possible existence of exceptions to this rule is recognized.

6. The resolution is about 8 inches, but for practical purposes 6 inches can be used.

7. Health hazard due to radiation from the source is very small with simple precautions.

8. Total weight of all equipment is about 30 pounds.

ACKNOWLEDGMENTS AND NOTE

This report is based upon work done since 1952. Many others have contributed to these activities, including Dr. Newton Underwood, Messrs. D. G. Harris, C. P. Fisher, E. E. Hood, and R. W. Swanson, whose cooperation is gratefully recorded. Appreciation is also due the National Science Foundation for financial aid and the North Carolina State College Physics Department for advice and loan of equipment.

The author will be pleased to receive inquiries regarding procurement of equipment or any other questions that may arise in connection with this report.

REFERENCES

1. Belcher, D. J.
The measurement of soil moisture and density by neutron and gamma-ray scattering. Highway Res. Board. Spec. Rpt. 2: 98-110. 1952.

2. Gardner, Wilford, and Kirkham, Don
Determination of soil moisture by neutron scattering. Soil Sci. 73: 391-401. 1952.

3. Goldberg, Irving, Trescony, L. J., Campbell, J. S., Jr., and Whyte, G. J. Measurement of moisture content and density of soil masses using radioactivity methods. Proc. Third Nat. Conf. on Clays and Clay Minerals, Publ. 395, pp. 516-548. 1955.

4. Holmes, J. W.
Calibration and field use of the neutron scattering method of measuring soil water content. Austr. Jour. Appl. Sci. 7: 45-58. 1956.

5. Knight, A. H., and Wright, T. W.
Soil moisture determination by neutron scattering. Proc. Radioisotope Conference Oxford 2: 111-122. 1954.

6. Stolzy, L. H., and Cahoon, G A.
A field-calibrated portable neutron rate meter for measuring soil moisture in citrus orchards. Proc. Soil Sci. Soc. Amer. 21: 571-574. 1957.

7. Stone, J. F., Kirkham, D., and Read, A. A.
Soil moisture determination by a portable neutron scattering moisture meter. Proc. Soil Sci. Soc. Amer. 19: 419-423. 1955.

8. Underwood, N., Van Bavel, C. H. M., and Swanson, R. W.
Note: A portable slow neutron flux meter for measuring soil moisture. Soil Sci. 77: 339-340. 1954.

9. Underwood, N., Van Bavel, C. H. M., and Swanson, R. W.
A portable rate meter and a source-counter assembly for measuring soil moisture content by neutron scattering. N. C. State College (Lithoprinted), 18 pp. 1954.

10. U. S. Department of Commerce.
Safe handling of radioactive isotopes. National Bureau of Standards Handbook 42. 1949.

11. U. S. Department of Commerce.
Radiological monitoring methods and instruments. National Bureau of Standards Handbook 51. 1952.

12. Van Bavel, C. H. M., Underwood, N., and Hood, E. E.
Vertical resolution in the neutron method for measuring soil moisture. Trans. Amer. Geoph. Union 35: 595-600. 1954.

13. Van Bavel, C. H. M., Underwood, Newton, and Swanson, R. W.
Soil moisture measurement by neutron moderation. Soil Sci. 82: 29-41. 1956.

14. Van Bavel, C. H. M., and Underwood, N.
Neutron and gamma radiation as applied to measuring physical properties of soil in its natural state. Proc. 6th Int. Cong. Soil Sci., Paris, B: 355-360. 1956.

NATIONAL AGRICULTURAL LIBRARY
1023085817